

Positioning on the Moon

with focus on

Moonlight LCNS - Lunar Communication and Navigation Services - “Lunar PNT Navigation System, Orbit Determination Solutions and Performance”

Cosimo Stallo, ESA Moonlight Navigation Principal System Engineer

We are going back to the Moon.....



... and stay there

LUNAR EXPLORATION: AN ON-GOING REVOLUTION



First Indian MOON LANDING ! FIRST Japanese MOON LANDING !



JAXA's SLIM



STARSHIP TEST 4

PUBLIC
.... PRIVATE

Race to Moon



NOVA-C

INTUITIVE MACHINES

FIRST Commercial MOON LANDING



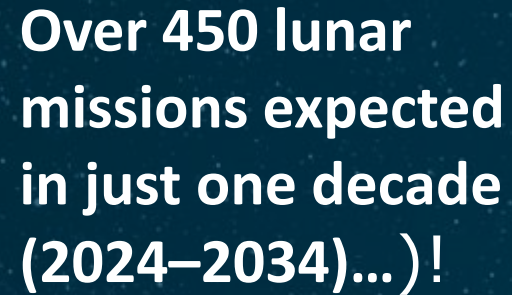
FIRST Chinese Lunar Sample return Mission (Moon Far Side)



FIRST Lunar COMM Relay Satellite in ELFO Orbit

ESA UNCLASSIFIED - Releasable to the Public





Solution: Set-up a dedicated Communication and Navigation infrastructures: boosting lunar exploration and lunar economy



First reception exploiting GNSS signal from Earth-LuGre

Navigation with GPS/Galileo from the Moon- some key challenges:

- low signal levels of GNSS signals (large distances and mostly coming from antenna sidelobes);
- Poor geometry – high DOP;
- limited access to navigation data;

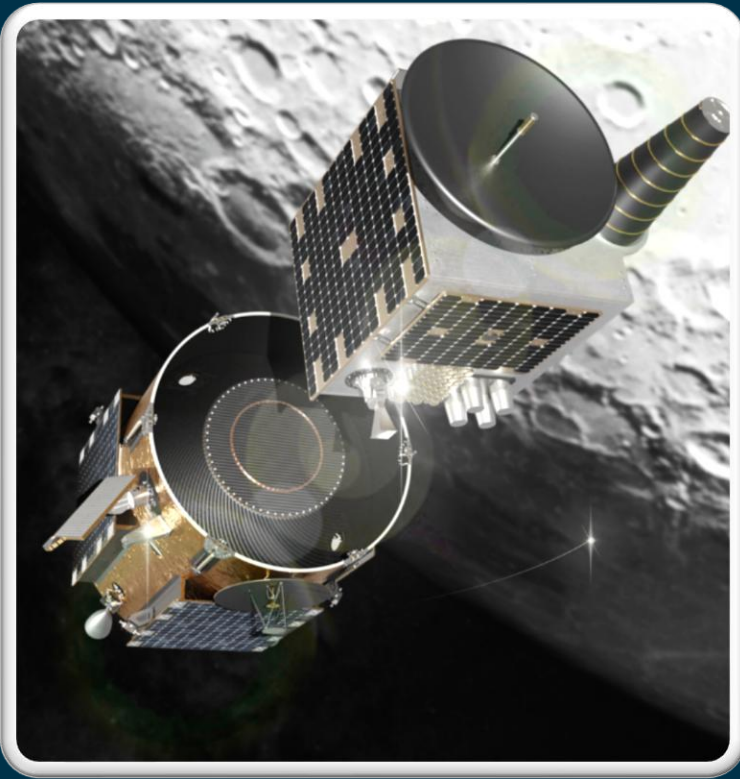
..and LuGre made it!



Artist's concept rendering of LuGRE aboard the Blue Ghost lunar lander receiving signals from Earth's GNSS constellations.
Courtesy of NASA/Dave Ryan

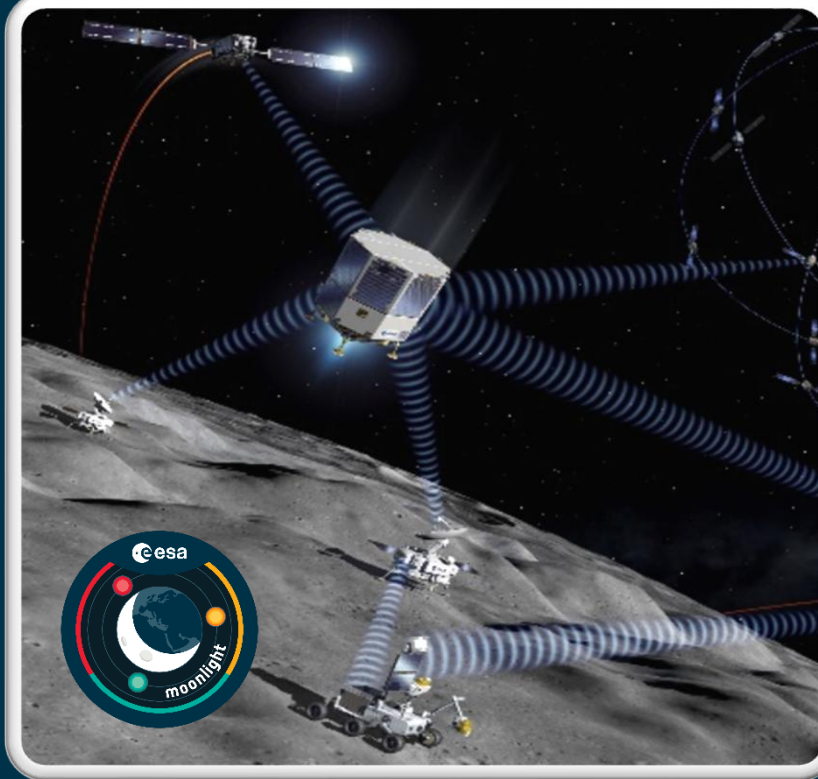
Lunar GNSS Receiver Experiment (LuGRE) payload, joint effort between NASA and the Italian Space Agency to demonstrate the viability of using existing GNSS (Global Navigation Satellite System) signals for positioning, navigation, and timing on the Moon

Roadmap For Lunar COMM and PNT Services



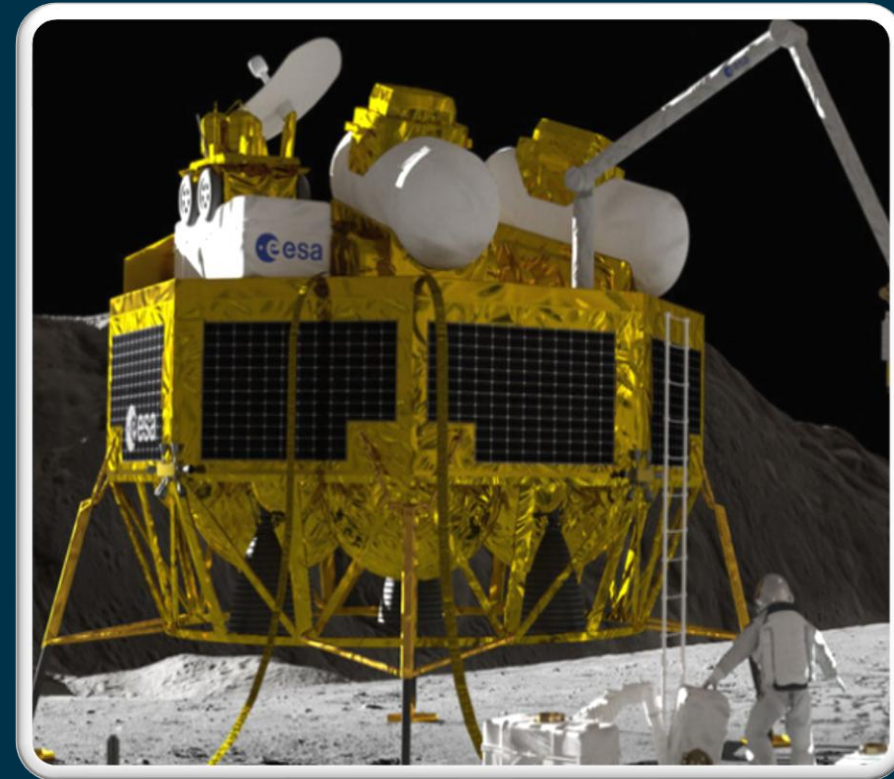
STEP 1: LUNAR PATHFINDER

(Launch 2026)



STEP 2: MOONLIGHT System

(Initial: 2028; Final: 2030)

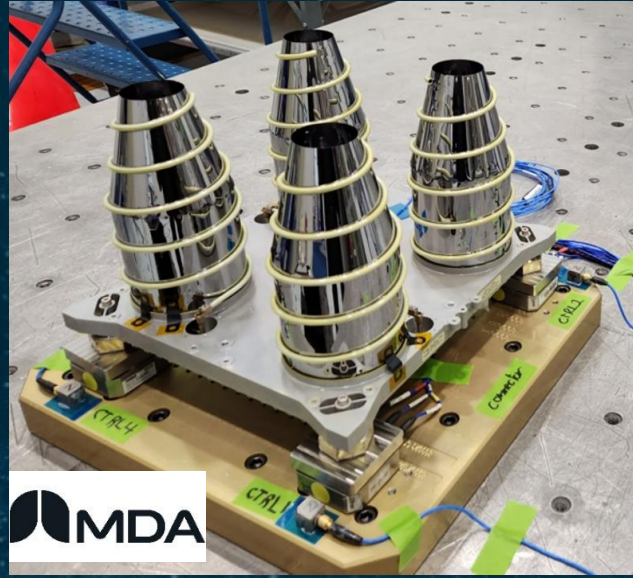


STEP 3: NOVAMOON: Local PNT Differential Station

Step 1- Lunar Pathfinder & GPS/GAL Reception



GNSS High-sensitive
receiver Flight unit



GNSS High-gain Antenna
Flight unit



Laser Retroreflector
Flight unit (NASA)

Demonstration of GPS/Galileo PNT on a Lunar orbiting satellite

Use of three ranging techniques (GNSS, Laser and X-band ranging) simultaneously on lunar orbit for orbit determination

Step 2- Moonlight LCNS



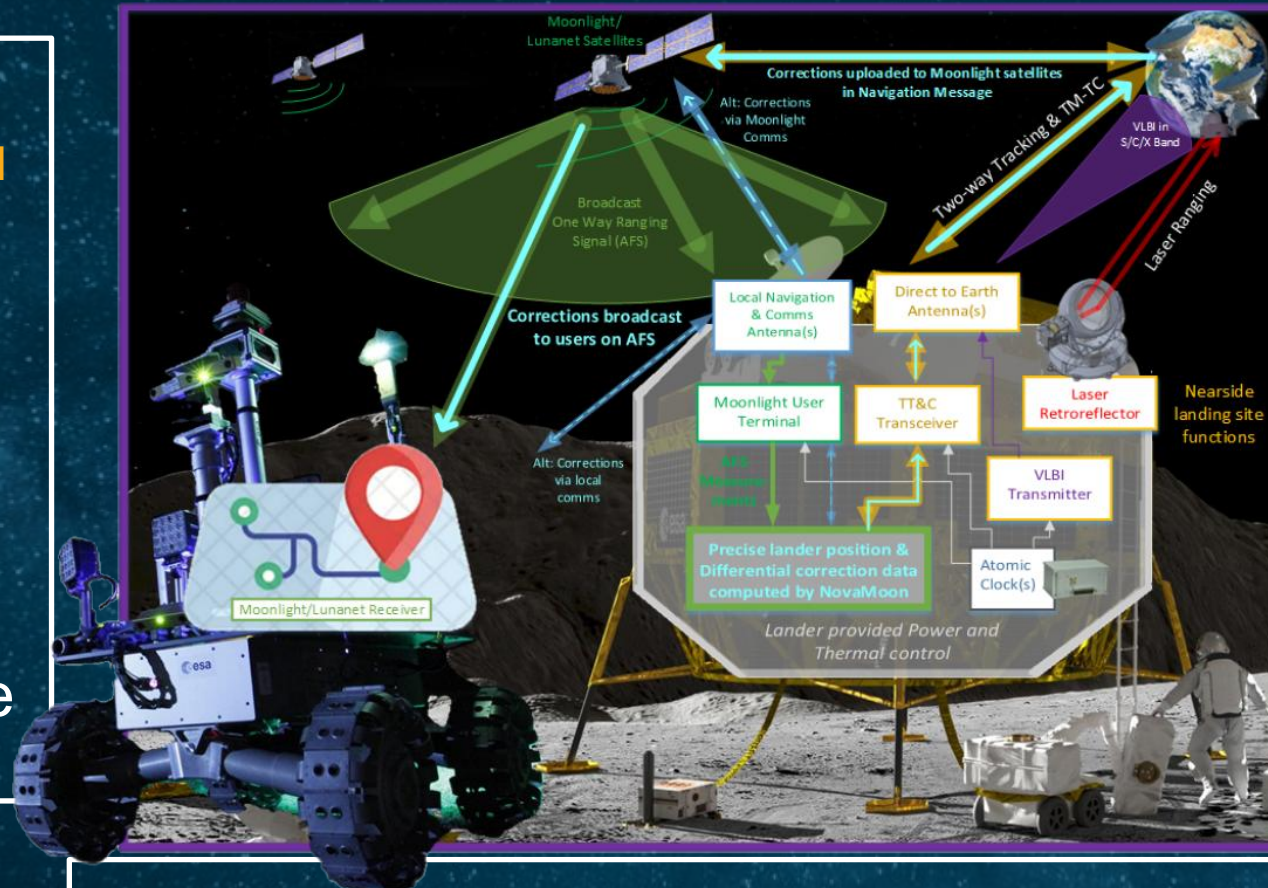
To provide dedicated constellation over Moon providing **interoperable Communications** and **Navigation Services** to support the current and next generations of **institutional** and **commercial Lunar explorers**

WHAT MORE? NovaMoon

1. Reference local differential station on the lunar surface

(augmenting and monitoring Moonlight and potentially other LunaNet compatible systems)

Sub-meter level accuracies over the whole Lunar South Pole



2. International “geodetic” Reference station on the lunar surface (4 collocated ranging techniques)

Towards an accurate Lunar Reference Frame realisation

3. International “Lunar Time-reference” Laboratory

Supporting experimentation and setting the basis for future lunar-base time realisations



Lunar landing enhanced accuracy using Moonlight + NovaMoon

NovaMoon, by providing precise differential corrections to the position and time of Moonlight satellites, will allow landing on the Moon with accuracies < 4 meters!!

	Mean	95 th perc.
3D error	3.6 m	8.4 m





- COM
- NAV
- User Terminal
- Ground Segment

Phase 2

- 1x COM Satellite
- 1x Nav Satellite
- User Terminal for Service Validation

- Ground Segment

Phase 3

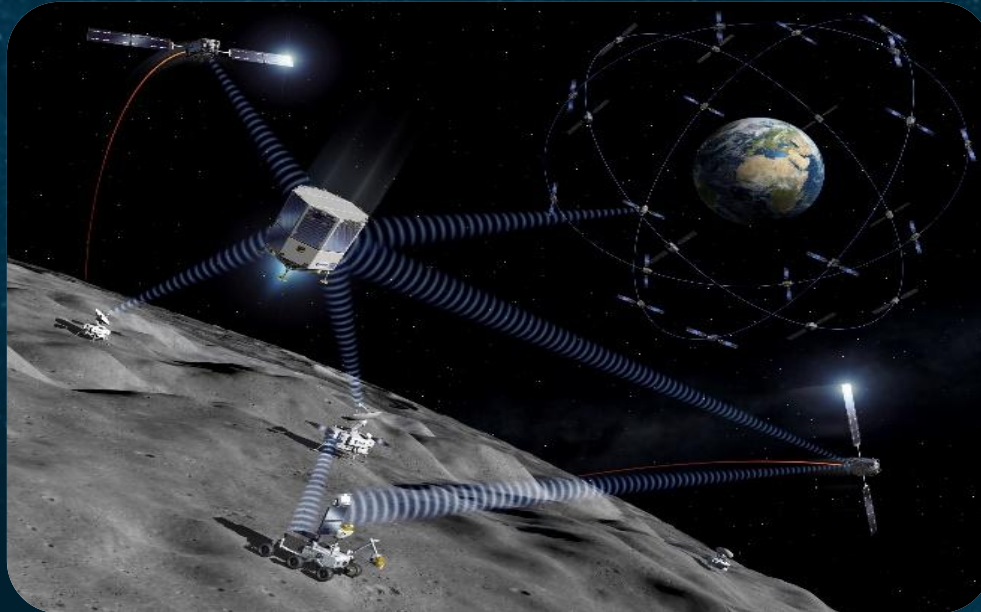
- 3x NAV Satellite

- Ground Segment Complement

Moonlight LCNS & Services Provision over Moon

Public-Private Partnership with a European consortia led by Telespazio Italy
ESA supporting infrastructure development and acting as Anchor customer

Contract KO held 11 Nov 2024



Data transport

Absolute Position

Tele-operations

Absolute Velocity

Audio/Video streaming

Universal time

Direct To Earth Service

Post-processing PVT

Over-the-top Services

LunaSAR return link

A dedicated constellation of satellites around the Moon providing commercial lunar communication and navigation services in two steps IOC (2028) and FOC (2030)

Lunar Satellite Navigation Main Challenges

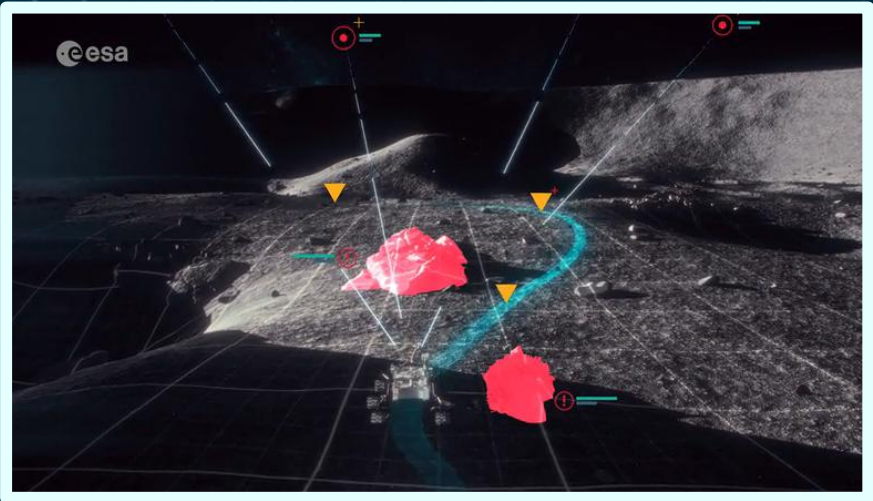
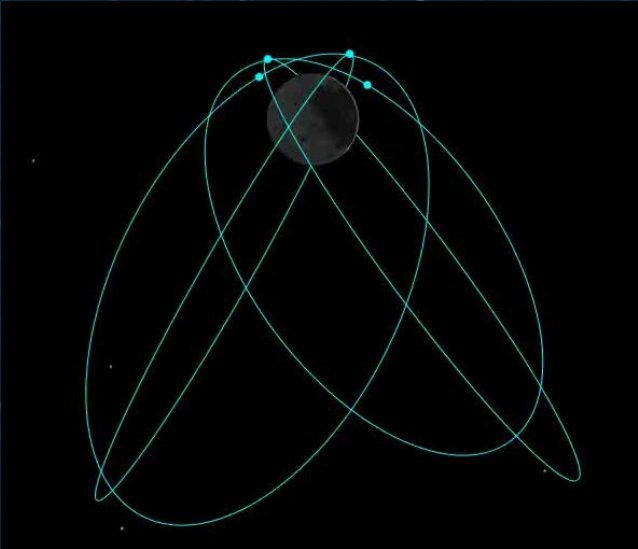
To face New challenges to enable Navigation in Lunar environment as:

- ///To design ad hoc satellite **orbits** (3-body problem (Earth, Moon, Sun)) mainly covering Moon South Pole optimizing main KPI navigation
- ///To define Lunar **reference frames**: definition of adequate lunar elevation models, datum, selenodetic and timing reference frames for high accuracy navigation services
- ///To design **radiation tolerant** solutions depending on the duration of the Navigation mission
- ///To define candidate **Orbit Determination and Time Synchronisation** techniques for Lunar Navigation
- ///To identify suitable **Clock technology**: High stability and miniaturised clocks
- ///To design **signal modulation techniques** specifically for lunar environment
- ///To define SIS ICD also ensuring **Interoperability and compatibility with other** future Lunar Missions (NASA/JAXA LunaNet)

Moonlight Navigation Mission Overview

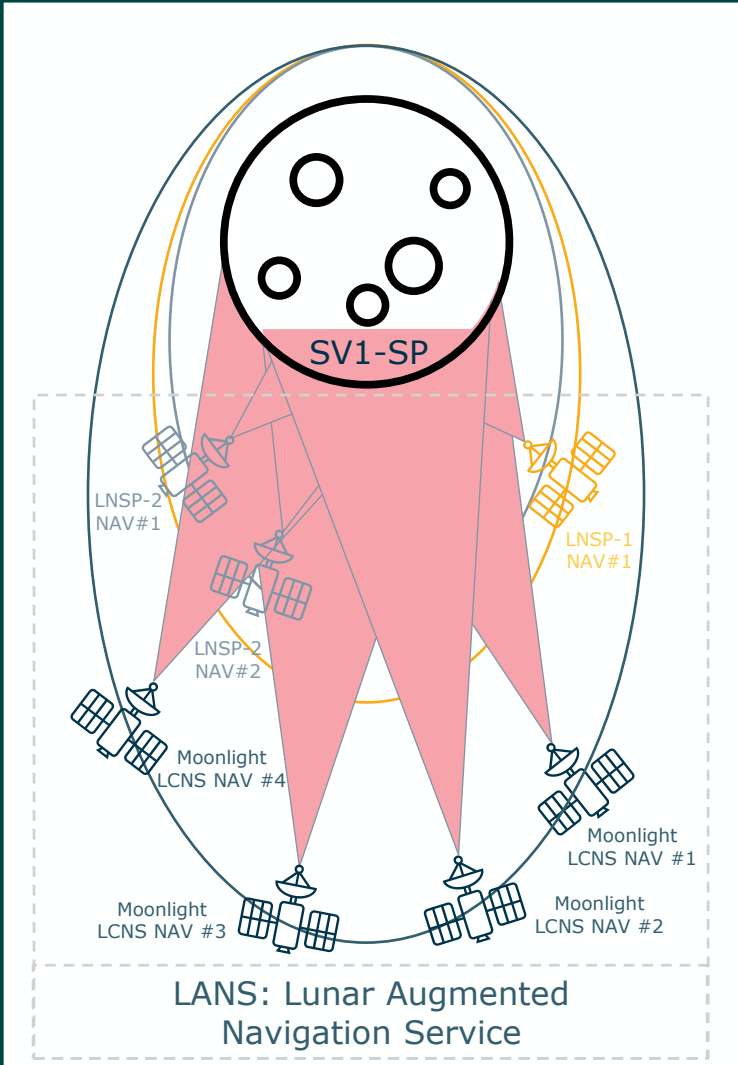
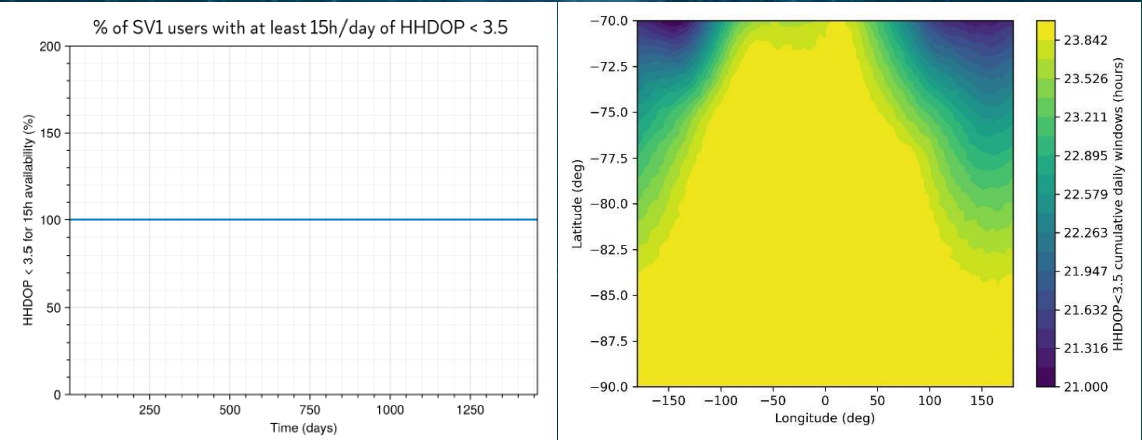


ELFO orbits (24 hrs period)



A minimum of 15 hours of continuous PNT service at South Pole every 24 h

Service	IOC service	FOC service
One-Way Ranging (OWR)	Initial Performance	Full Performance
Position, Velocity and Time (PVT)	Not provided	Full Performance
Time Dissemination service (TS)	Not provided	Full Performance
Two-way Measurements (TWM)	Initial Performance	Full Performance
PVT post processing	Initial Performance	Full Performance
Service availability and performance prediction	Full Performance	Full Performance



Moonlight LCNS High-level Mission and Service Drivers



Supporting
Commercial &
Institutional Missions



Interoperable
LunaNET
Standards



IOC in 2028
FOC in 2030
Evolutions 2030+



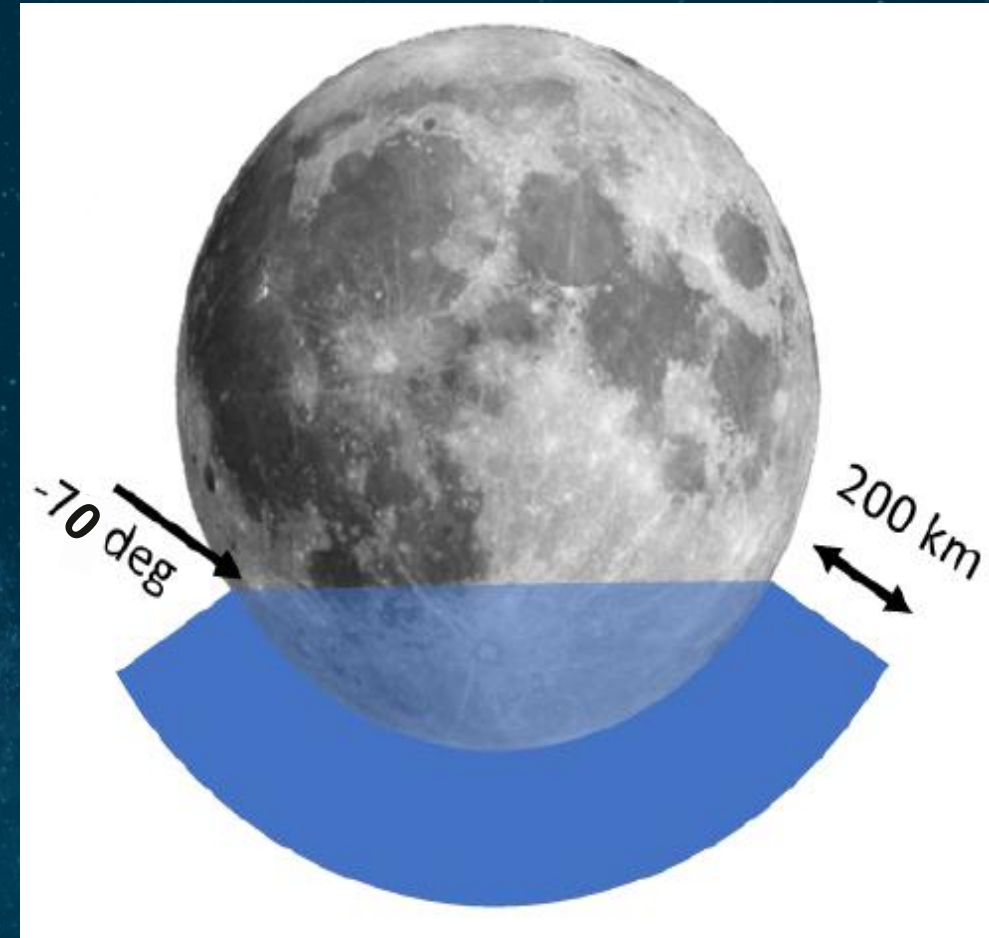
A Scalable System



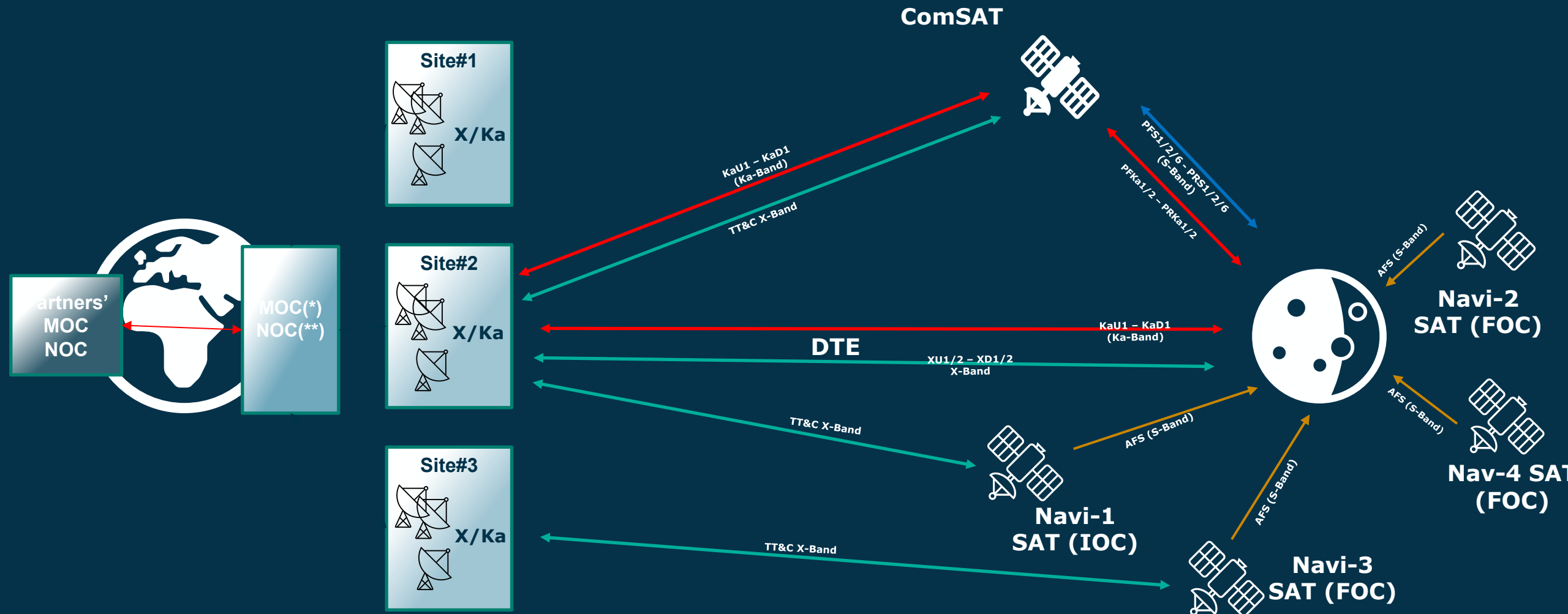
Supporting all Mission
Phases



Optimised
For South Pole
services
[70-90° South]



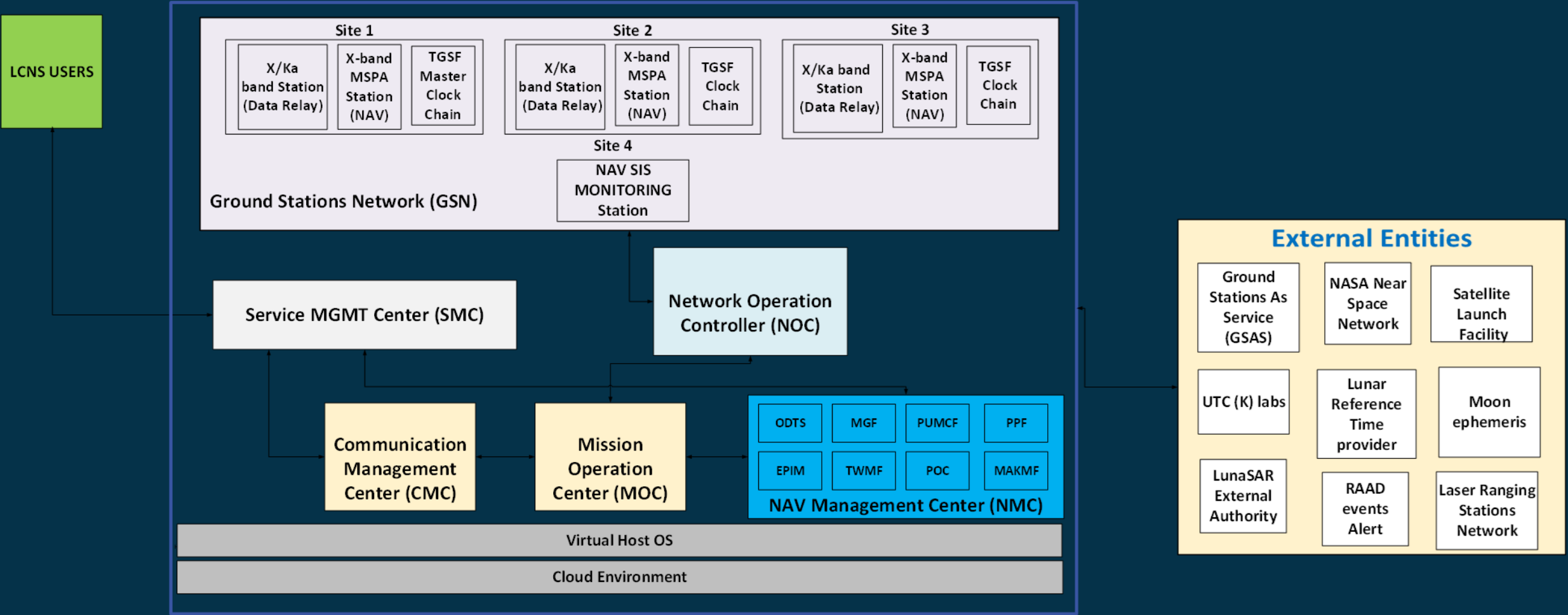
Moonlight: Mission Architectural Concept



(*) MOC Mission Operation Centre
(**) NOC Network Operation Centre



Moonlight Earth Ground Segment Architecture



- 4 NAV SATs simultaneously visible and tracked from the same ground antenna (diameter<1m) in three different EGS GSN TT&C stations located about 120° in longitude (Italy, USA and AUS)
- Each NAV SAT with onboard Steerable MGA and ICU-x implementing ranging and Two-Way Time Transfer with each EGS GSN TT&C station
- Network of three Time Generation and Synchronisation stations (TGSF) collocated at each EGS GSN TT&C with an atomic clock (1 master and 2 secondary)

The diagram illustrates the LCNS System Architecture. On the left, Earth is shown with three ground stations: Ground Station #1, Ground Station #2, and Ground Station #3. Dashed lines labeled 'synchronous' connect these stations to the Earth's surface. A light blue box at the top left contains the position error formula:

$$SISE_{pos} = \sqrt{(x - \tilde{x})^2 + (y - \tilde{y})^2 + (z - \tilde{z})^2 + (ct - \tilde{ct})^2} < 10 \text{ m (95\%)} \text{ over any 24 hours}$$

Four green arrows labeled 'X band TT&C*' point from the ground stations to the lunar navigation satellites. The satellites are labeled: LSS NAV #1 (IOC), (FOC) LSS NAV #2, LSS NAV #3 (FOC), and LSS NAV #4 (FOC). A red dashed arrow labeled 'AFS S-band*' points from LSS NAV #3 to the lunar lander on the Moon. A clock icon labeled 'miniRAFS' is shown near LSS NAV #4. Frequency ranges are listed at the bottom: *U/L: [7190-7235] GHz, *D/L: [8450-8500] GHz, and *[2483.5-2500] MHz. The text 'LCNS System Time (LST) generated by the Master Clock Station and steered to UTC' is at the bottom center.

SISE versus AoD Simulation Results: Main assumptions

- ❑ 3 GSN stations on Earth: Malargue, New Norcia, Cebreros (Example)
- ❑ MSPA for each station -> visibility of each satellite almost 24h per day
- ❑ X band only (no SBI)

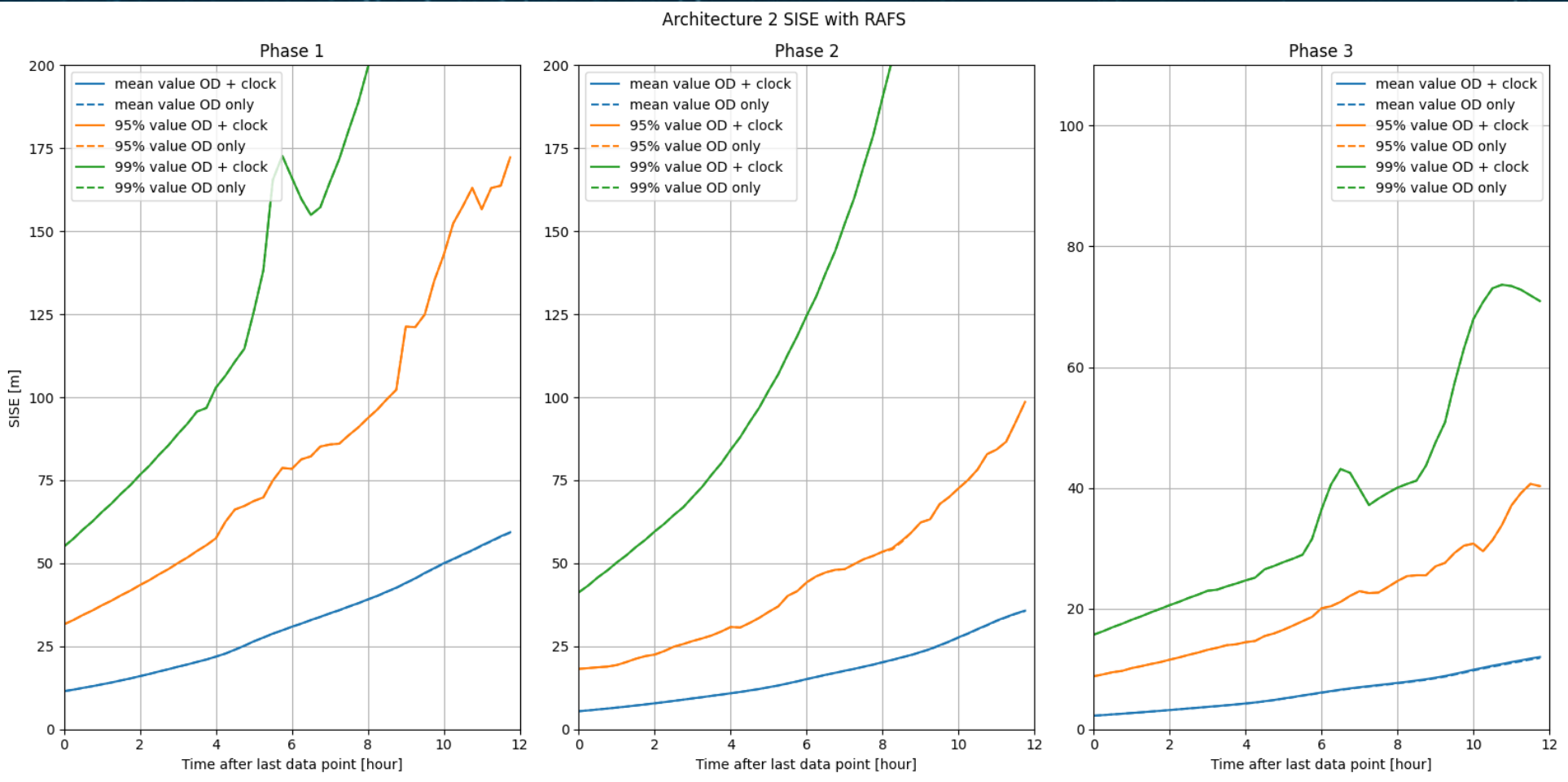
Real-time
 ≈ 100 m (95%)

Different phases considered for media calibration of the Earth station

1. **Phase 1:** Initial deployment
 - a. Ionosphere: NeQuick model
 - b. Troposphere: barometer calibration for the dry troposphere
2. **Phase 2:** Augmentation 1
 - a. Ionosphere: GNSS dual frequency data
 - b. Troposphere: GNSS delta-tropospheric calibration
3. **Phase 3:** Augmentation 2
 - a. Ionosphere: GNSS dual frequency data
 - b. Troposphere: use of Advanced WVR (AVWR)

Case information	Phase 1	Phase 2	Phase 3
Wet troposphere calibration	Uncalibrated	GNSS (20%)	WVR (10%)
Ionosphere calibration	NeQuick (50%)	GNSS (10%)	
Empirical acceleration time step	RTN: 24 h or Piecewise-constant: 8h		
Empirical acceleration a-priori uncertainty	1.5x10 ⁻⁸ m/s ² (5% of SRP)		7.5x10 ⁻⁹ m/s ² (2.5% of SRP)
Unmodelled antenna dish area	0.40 m ² (100%)		0.20 m ² (50%)

SISE vs AoD



Real-time

~ 100 m (95%)

2h AoD
100 m (95%)

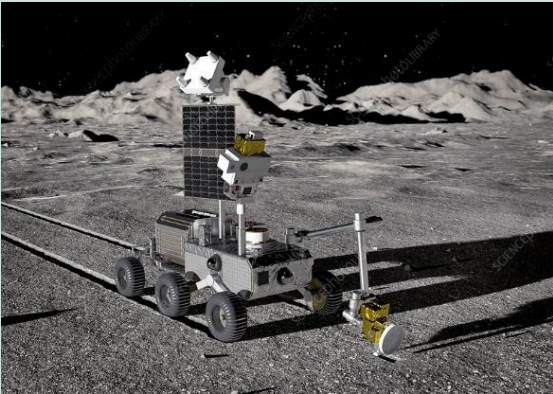
SISE is about 10 m (95%)
versus AoD = 2 hours



Moonlight FOC LCNS High-level PNT Performances

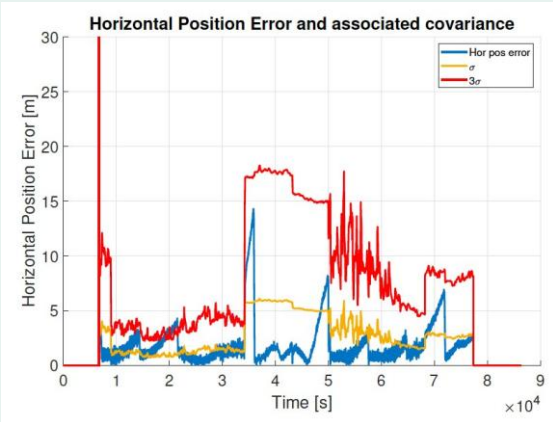


Surface Rover



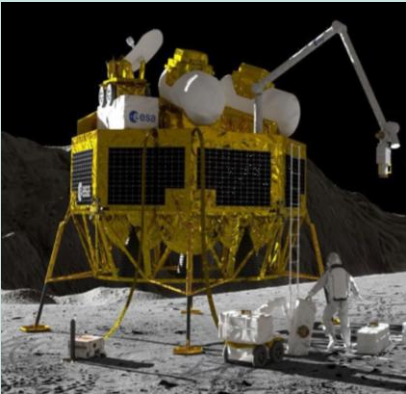
Real time
< 10 m (95%)

Post-processing
< 3 m (95%)



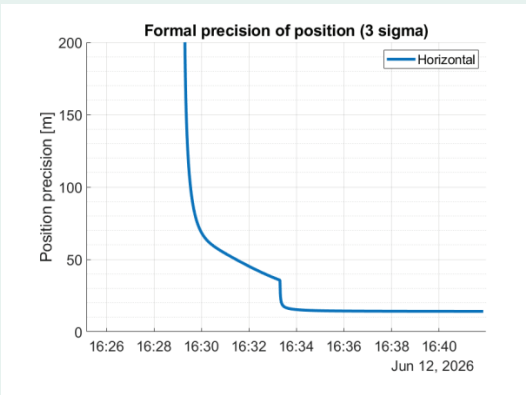
3-5 meters

Lunar Lander



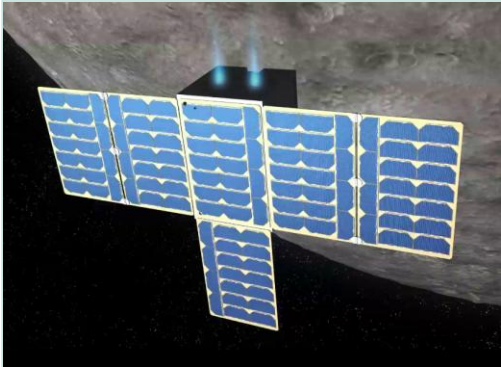
< 50 m (95%)

Landing
accuracy



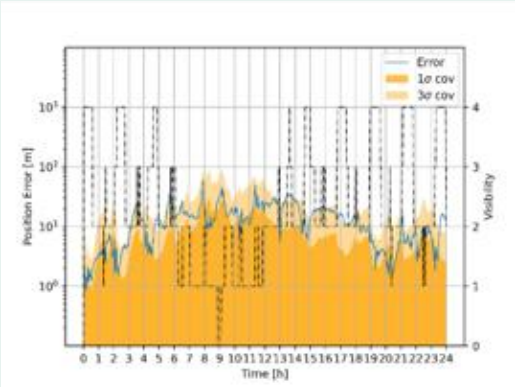
~20 meters

Lunar Orbiter



Real time
< 100 m (95%)

LLO accuracies

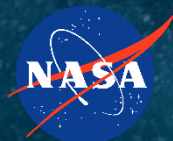


30-60 meters

ALSO CONFIRMED BY INDUSTRY (AT PDR Stage)



LunaNetHigh-levelCoordination/Governance



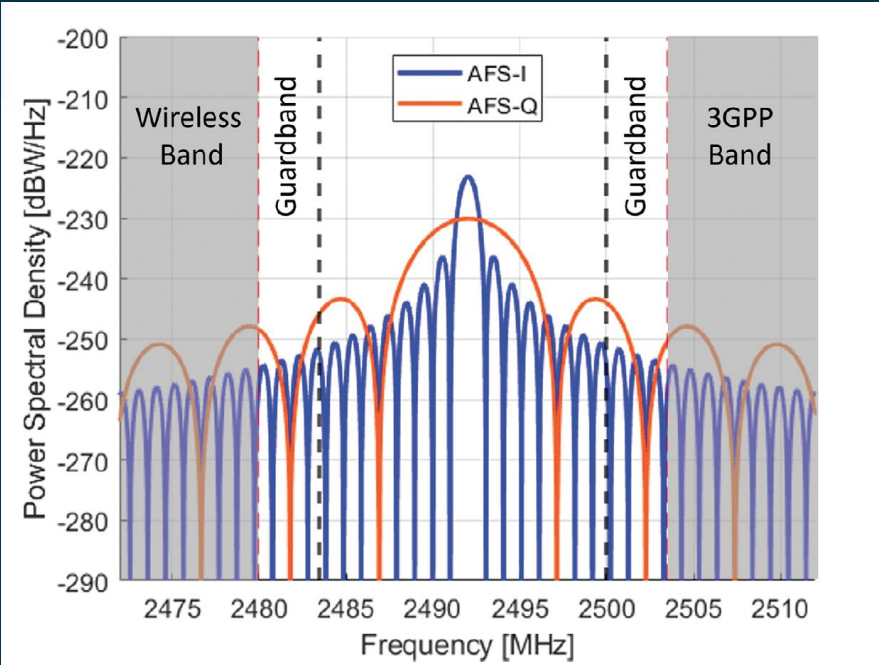
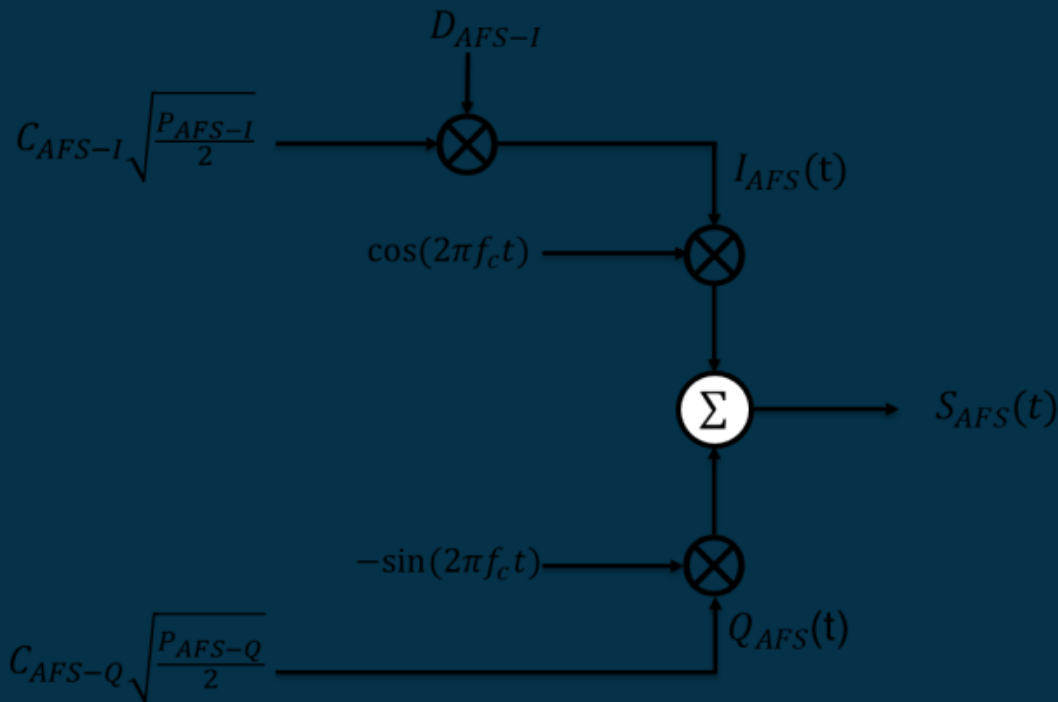
Version 1

Noted as Applicable Document 1 [AD1 Vol-A] in LNIS V5

and ongoing
international effort
toward v6...

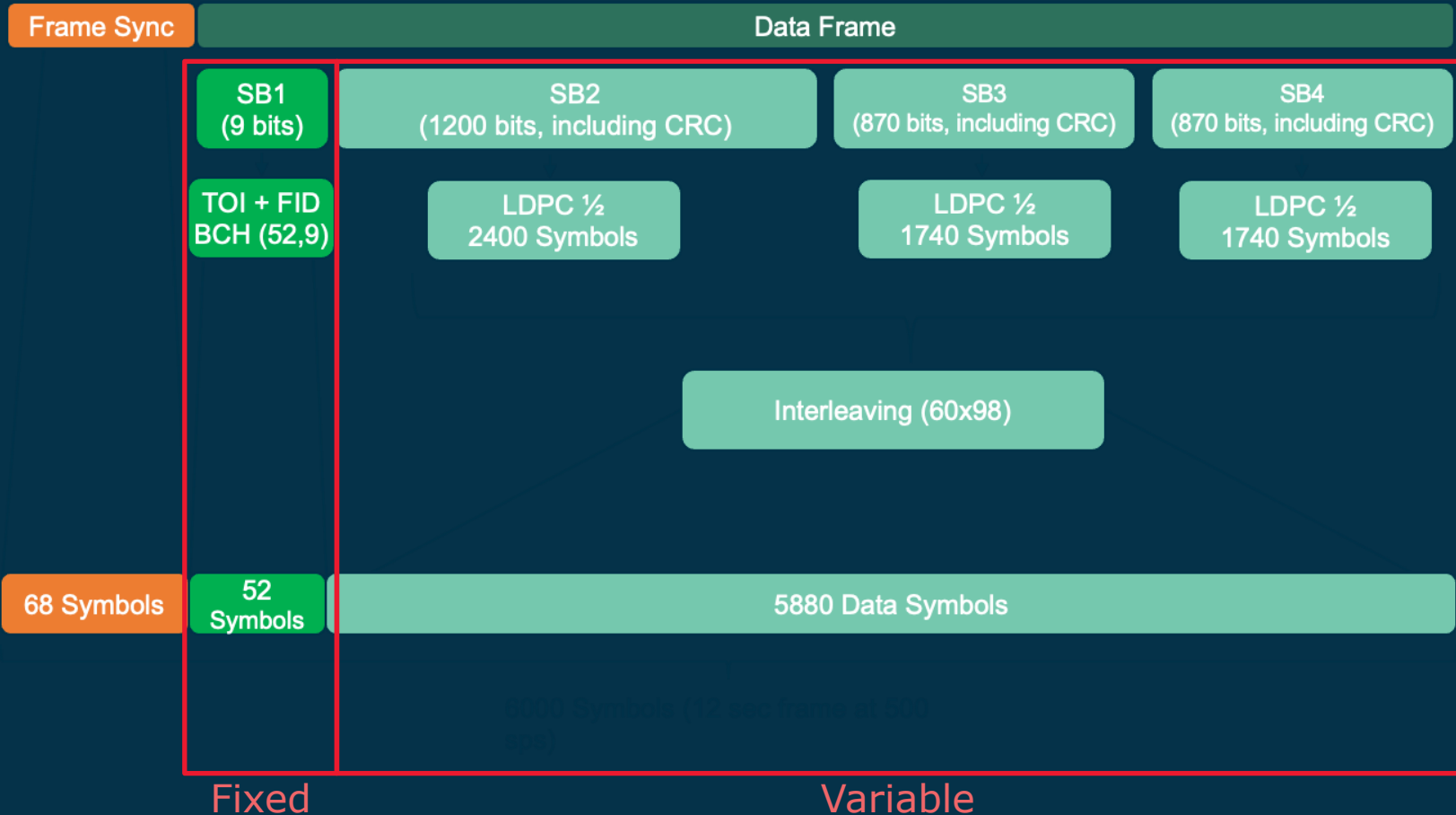
ESA UNCLASSIFIED - Releasable to the Public

LunaNet – Augmented Forward Signal Modulation



	Modulation	Primary Code	Secondary Code	Tertiary Code	Data Rate
AFS-I (Data)	BPSK(1)	2046 chips / 2 ms	n/a	n/a	500
AFS-Q (Pilot)	BPSK(5)	10230 chips / 2 ms	4 chips / 8 ms	1500 chips / 12 sec	n/a

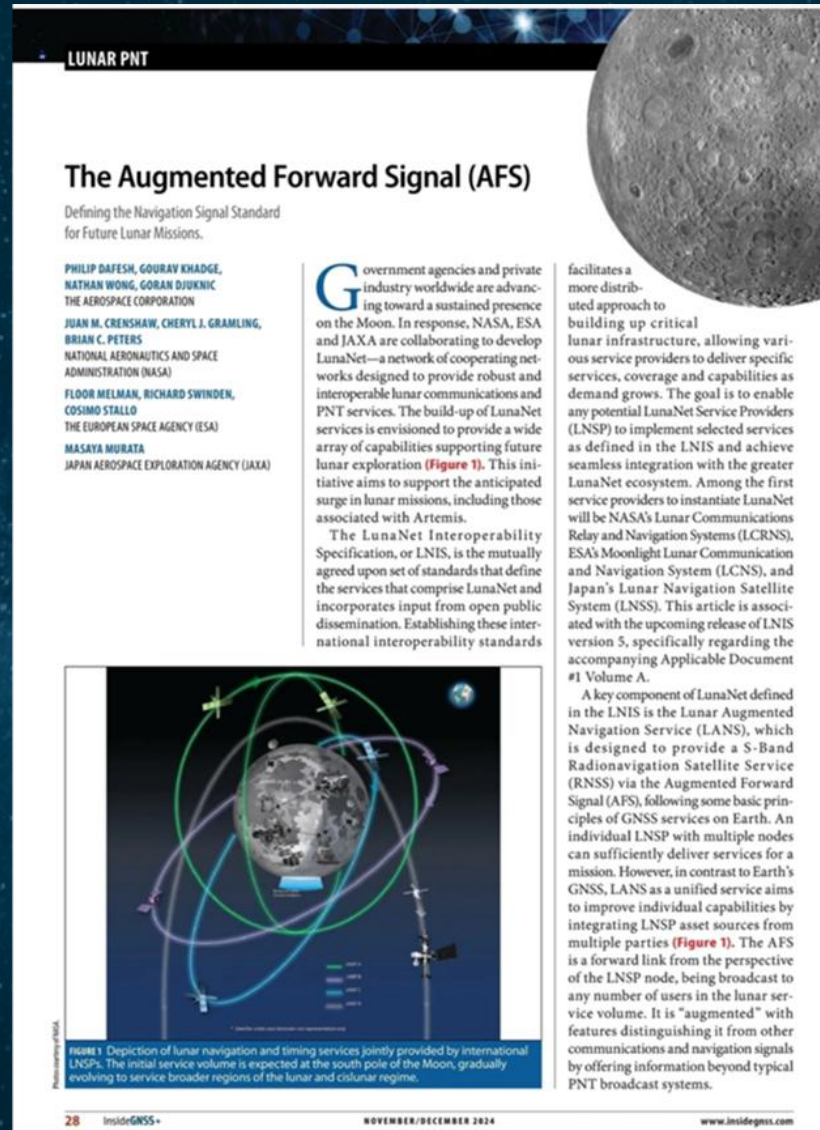
LunaNet – AFS Navigation Message



Also see publications:

ION GNSS+ 2023 (P. Giordano et al, LunaNet Position, Navigation, and Timing Services and Signals, Enabling the Future of Lunar Exploration)

ITM/PTTI 2025 (P. Dafesh et al, The Design of a Flexible, Interoperable Navigation Signal for Future Lunar Missions)



LunaNet 1.0 Interoperability Frequency Plan¹

The diagram illustrates the frequency plan for the LunaNet 1.0 system, showing communication links between Earth, the Moon, and lunar orbiters. The Earth is on the right, the Moon is in the center, and lunar orbiters are shown in orbit around the Moon. The Moon's surface is depicted with a rover and a lander. The diagram shows various communication links, including direct point-to-point links and broadcasts, with associated frequency ranges.

Legend:

- LANS – Lunar Augmented Navigation Service
- LO – Lunar Orbit
- LS – Lunar Surface
- ▶ Broadcast
- Direct Point-to-Point link

Notes:

1. Consistent with the IOAG Architecture, NASA-SCaN Lunar Architecture, ICSIS and SFCG REC 32-2R5
2. Per SFCG REC 41-1, lunar region links with occupied bandwidth < 6 MHz may use S-, X-, or Ka-band, while lunar region links with occupied bandwidth ≥ 6 MHz should use Ka-band only
3. Refer to SFCG REC 42-1 for specific frequency ranges to be used for space-to-space links (proximity and intersatellite)



UNION INTERNATIONALE DES TÉLÉCOMMUNICATIONS
BUREAU DES RADIOCOMMUNICATIONS

INTERNATIONAL TELECOMMUNICATION UNION
RADIOCOMMUNICATION BUREAU

UNIÓN INTERNACIONAL DE TELECOMUNICACIONES
OFICINA DE RADIOCOMUNICACIONES

© I.T.U.

RÉSEAU À SATELLITE SATELLITE NETWORK RED DE SATELITE		MOONLIGHT LCNS LSS-NAV		SECTION SPÉCIALE N° SPECIAL SECTION No. SECCIÓN ESPECIAL N.º		API/A/14070	
				BR IFIC / DATE BR IFIC / DATE BR IFIC / FECHA		3053 / 19.08.2025	
ADM. RESPONSABLE RESPONSIBLE ADM. ADM. RESPONSABLE		I		LONGITUDE NOMINALE NOMINAL LONGITUDE LONGITUD NOMINAL		NGSO	
RENSEIGNEMENTS REÇUS PAR LE BUREAU LE / INFORMATION RECEIVED BY THE BUREAU ON / INFORMACIÓN RECIBIDA POR LA OFICINA EL				11.06.2025			

Ces renseignements reçus par le Bureau des radiocommunications, en application du numéro 9.1/9.2 du Règlement des radiocommunications, sont publiés conformément au numéro 9.2B.

This information, received by the Radiocommunication Bureau pursuant to No.9.1/9.2 of the Radio Regulations, is published in accordance with No. 9.2B.

Esta información, recibida por la Oficina de Radiocomunicaciones con arreglo al número 9.1/9.2 del Reglamento de Radiocomunicaciones, se publica de acuerdo con lo dispuesto en el número 9.2B.

Une administration qui estime que des brouillages inacceptables risquent d'être causés à ses réseaux ou à ses systèmes à satellites existants ou en projet communique à l'administration qui a demandé la publication des renseignements ses observations, avec copie au Bureau des radiocommunications, dans le délai indiqué ci-après.

Any administration which believes that unacceptable interference may be caused to its existing or planned satellite networks or systems shall communicate its comments to the publishing administration, with a copy to the Radiocommunication Bureau, by the deadline indicated below.

Cualquier administración que estime que se podría causar interferencia perjudicial a sus redes o sistemas de satélites existentes o planificados deberá comunicar sus comentarios a la administración que publica, con copia a la Oficina de Radiocomunicaciones, en el plazo que se indica más abajo.

DATE LIMITE POUR LA RÉCEPTION DES COMMENTAIRES EXPIRY DATE FOR THE RECEIPT OF COMMENTS FECHA LÍMITE PARA LA RECEPCIÓN DE LOS COMENTARIOS		19.12.2025	
--	--	------------	--

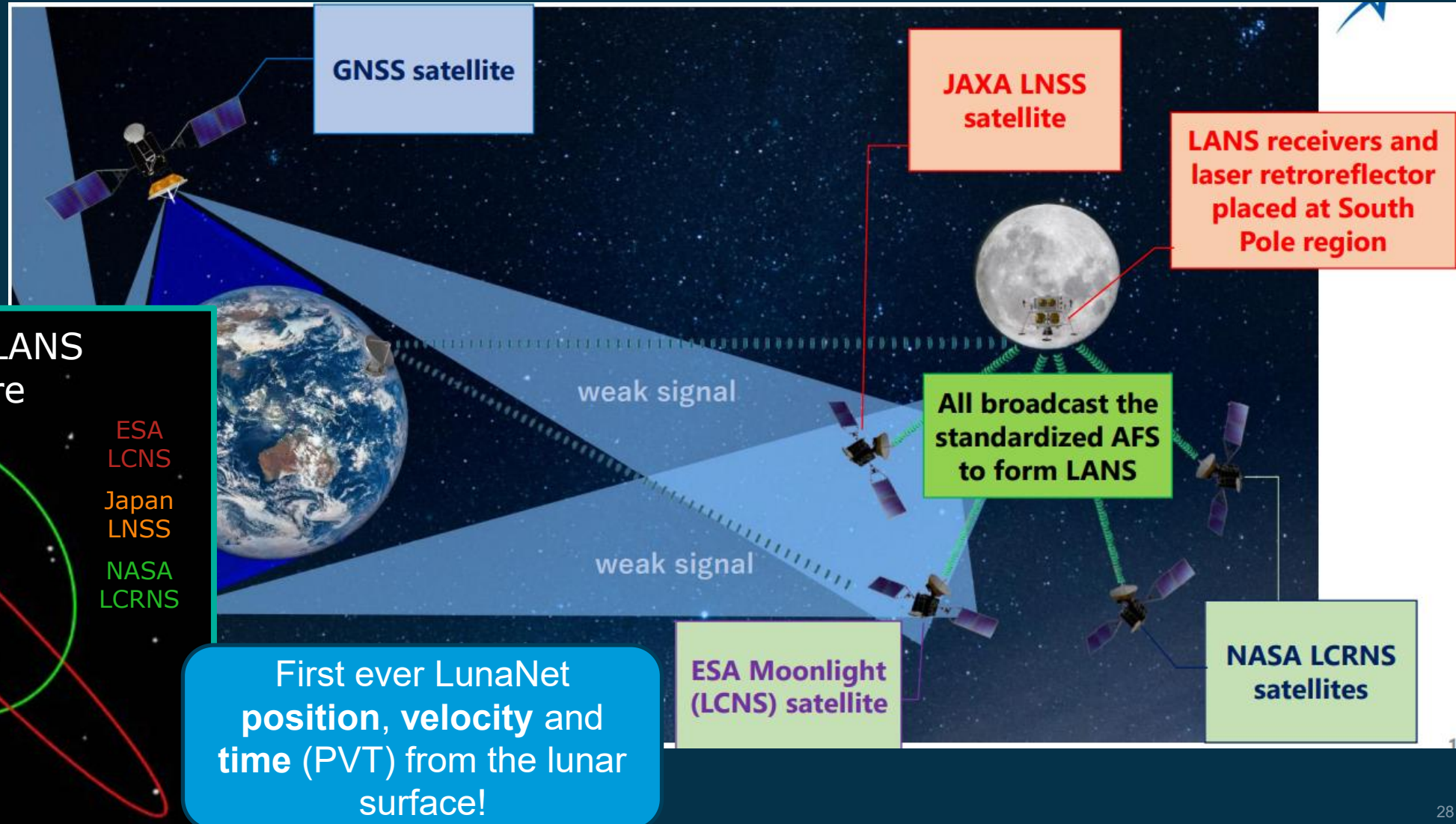
Page / Página / 頁 / ctp. / الصفحة 1



LunaNet Interoperability Demo Mission with JAXA and NASA



Using Moonlight IOC capability and embarking ESA LANS receiver on JAXA lander mission to perform Interoperability Demo in 2029



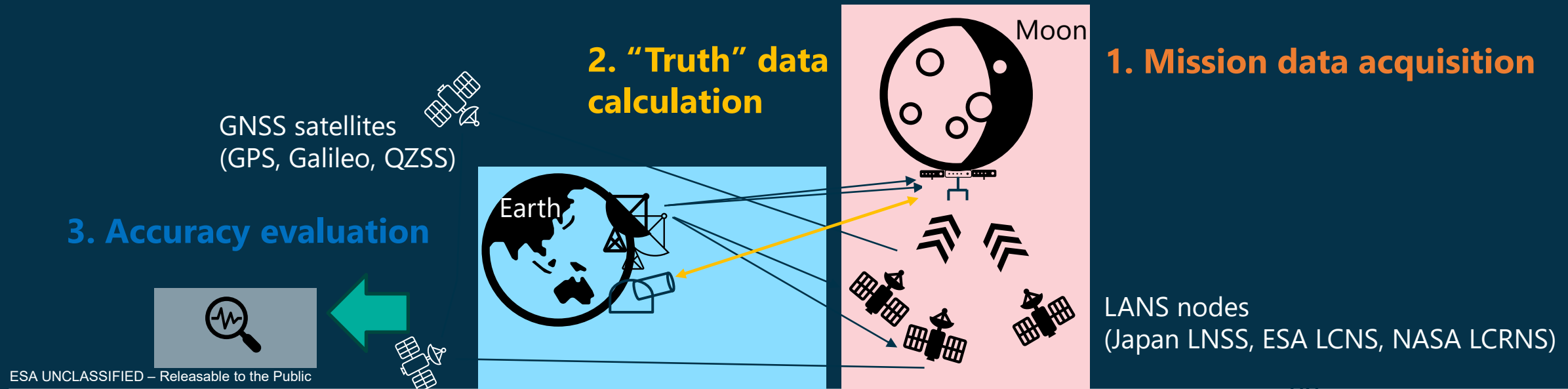
Notional IOC LANS Architecture

ESA
LCNS
Japan
LNSS
NASA
LCRNS

LunaNET interoperability and PNT demonstration – Three major steps



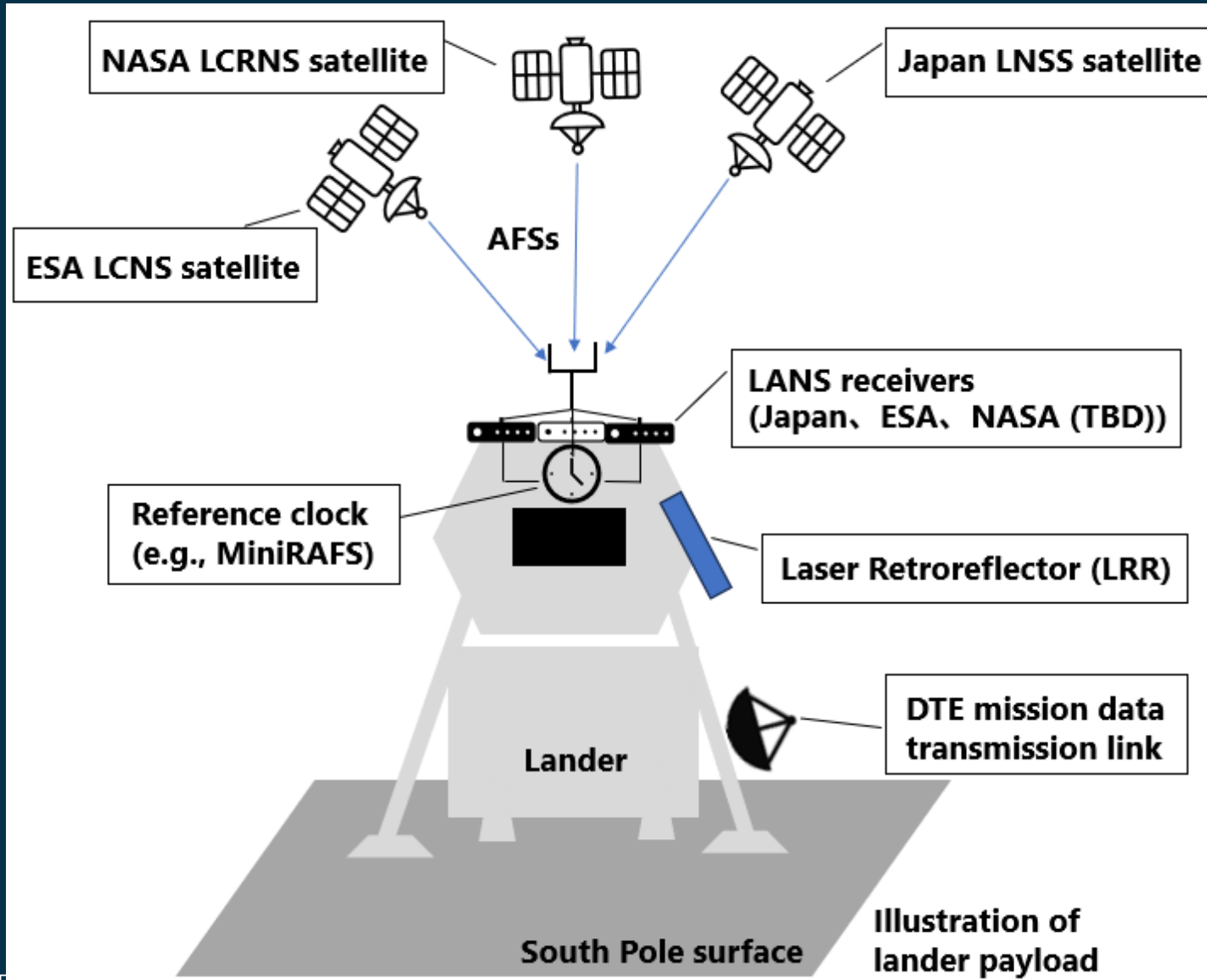
1. Acquisition of mission data (observations from the AFSs and terrestrial GNSS, LANS receiver PVT solutions) in Moon's environment
2. Calculation of "truth" data (precise LANS satellite orbits and clocks, precise LANS receiver positions and clocks) by Earth stations and laser stations
3. Evaluation of SISEs for LNSP nodes and LANS PVT accuracy by comparing the acquired mission data with the calculated "truth" data



ESA UNCLASSIFIED – Releasable to the Public

29

The planned LunaNET interoperability demonstration payload



The LANS receivers connected to the reference clock receive all broadcast AFSs

The LANS accuracy demonstration needs the “truth” data with a target accuracy at one-meter-level for both the receiver’s location and clock determination results

To achieve this level of accuracy, Laser retroreflector (LRR) and the MiniRAFS are both necessary

Other optional payloads are also under consideration such as integrated GNSS reception with LANS receivers and using DTE link for time transfer

Moon seen as next frontier: support to Moon missions is essential in terms of communication and navigation capabilities

European effort to be part of Moon exploration and beyond relying on....

- ❑ strong Industrial contribution and technological excellence
- ❑ investment supporting the effort required to develop the assets and access the lunar market
- ❑ ...International cooperation for interoperability and standardization in the new Moon environment

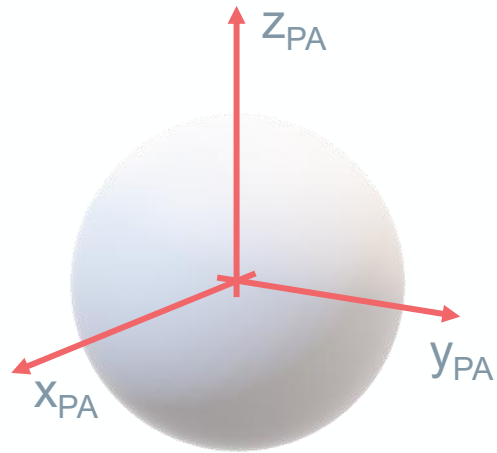
Questions???



LunaNET on Reference Frames

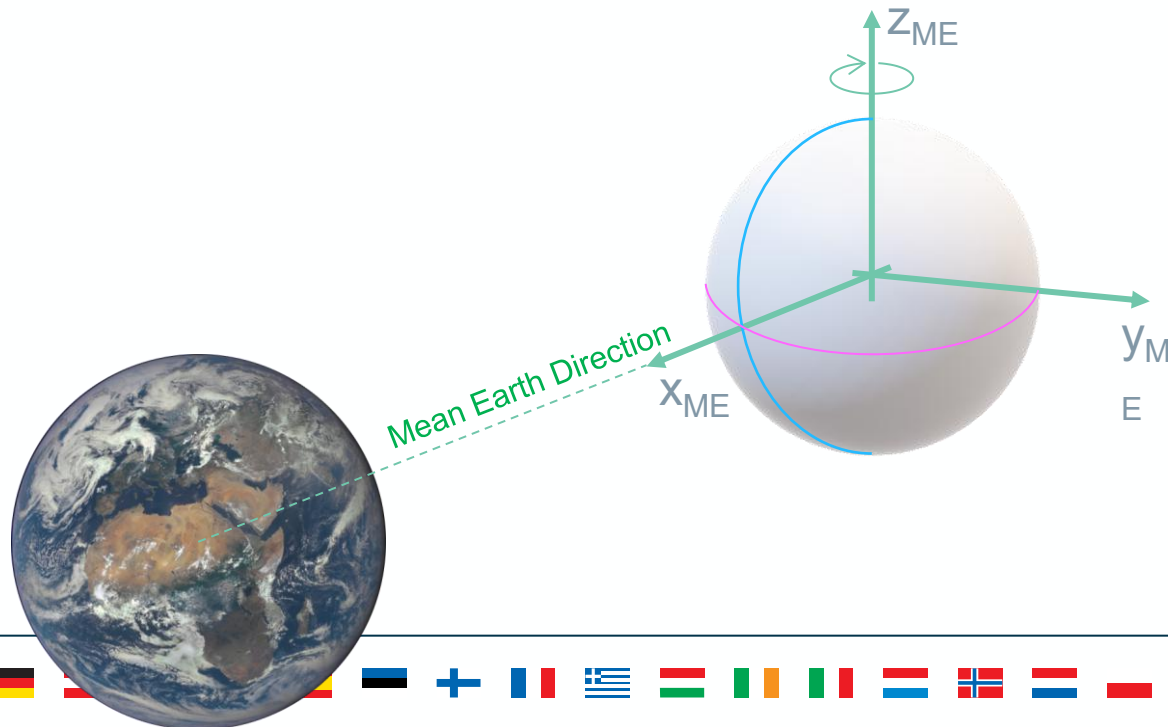
The long-term perspective of LunaNet is to adopt reference systems/frames generated with the contribution of the whole scientific community under the auspices of official international organizations.

	Inertial System	Fixed System	Reference Frame
The Earth	GCRS (Geocentric Celestial Reference System)	ITRS (International Terrestrial Reference System)	ITRF (International Terrestrial Reference Frame)
The Moon	LCRS (Lunar Celestial Reference System)	ILRS (International Lunar Reference System)?	Short term: PA, ME Long term: ILRF (International Lunar Reference Frame)?



$$\longleftrightarrow I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$

The tide-free lunar tensor of inertia is diagonal in the PA system



Principal Axis (PA) reference system

- It is a selenocentric reference system defined by the principal axes of the lunar tensor of inertia with constant tide contributions
- Natural reference system for dynamical studies including e.g., gravity field determination
- Relation to LCRS:

3D rotation parametrized by a precession angle (ϕ), a nutation angle (θ), and a proper rotation angle (ψ)

$$\vec{x}_{PA} = R_z(\psi)R_x(\theta)R_z(\varphi)\vec{x}_{LCRS}$$

Mean Earth Reference System

- Right-handed spherical coordinate system:
 - origin in the Moon centre of mass
 - z-axis aligned with the mean rotational axis
 - x-axis directed to the mean sub-Earth point
 - the y-axis completes the right-handed orthogonal system.
- Adopted since the beginning of lunar observation, the ME system is typically used for data archiving and for product distribution (e.g. topography and maps).

LunaNet recommends PA (Principal Axis) versus ME (Mean Earth) in the short term for the LunaNet PNT scope.

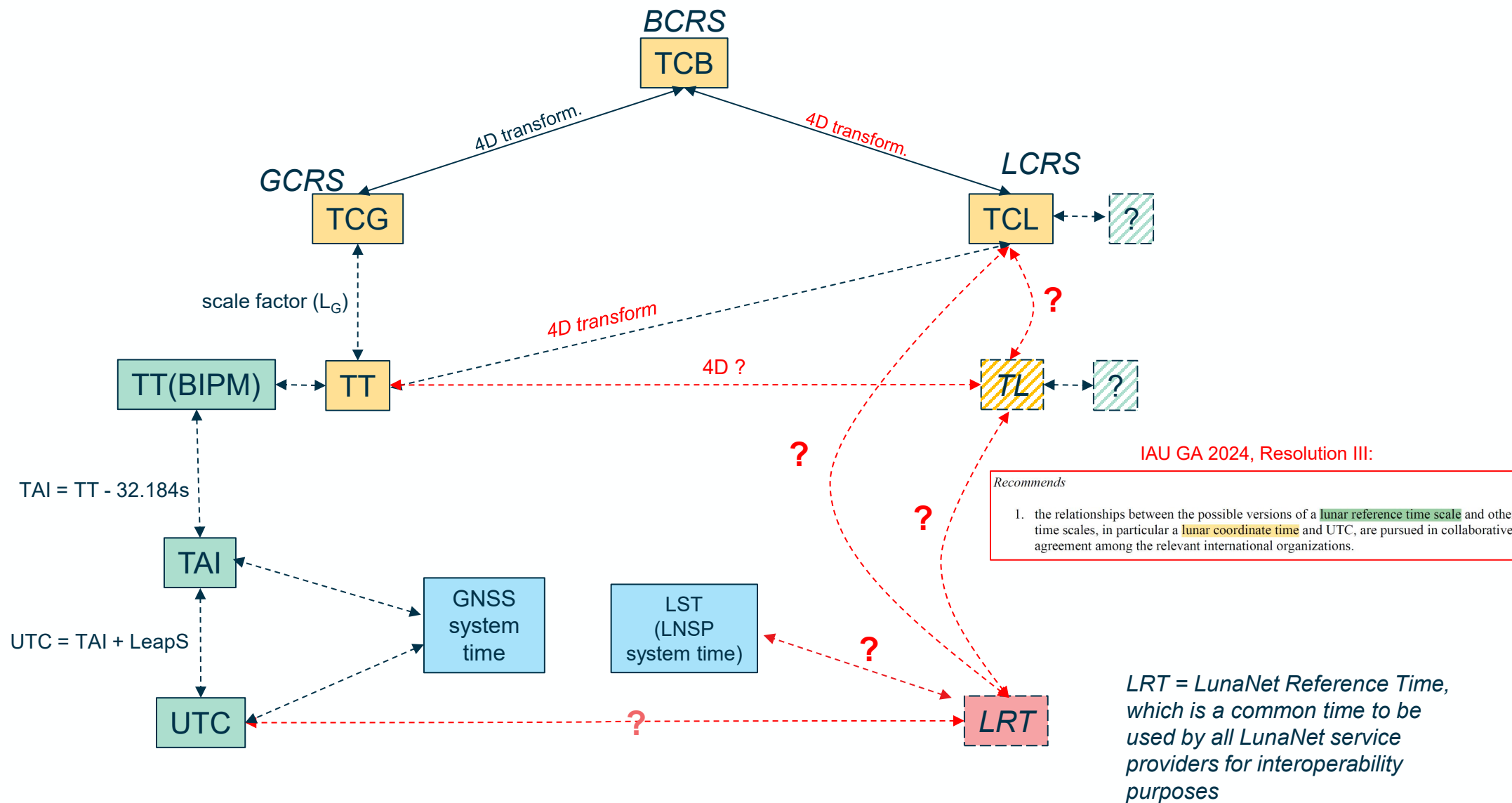
❑ Reason 1: ME is derived from PA

(The PA → ME transformation is realised by three static Euler angles that shall be always distributed together with the realization of the primary frame (PA)).

$$\begin{aligned} \mathbf{r}_{\text{MER,DE421}} = & \mathcal{R}_x(-0^{\circ} 2785) \mathcal{R}_y(-78^{\circ} 6944) \\ & \times \mathcal{R}_z(-67^{\circ} 8526) \mathbf{r}_{\text{PA,DE440}}. \end{aligned}$$

❑ Reason 2: PA is more easily applied to other celestial bodies.

Defining Time on the Moon...



TCL is the **Lunar Coordinate Time** at the centre of the moon, in analogy with TCG at earth centre

And In line with IAU GA 2024 Resolution III terminology, the following options are being considered by Timing Community:

- Option 1: LRT is a **lunar reference time scale** that is on the lunar “geoid”, in analogy with UTC
- Option 2: LRT is a **lunar reference time scale** that is at the moon centre, with no analogy with Earth case

Noting that IAU GA Res III is titled:

Resolution on the establishment of a coordinated lunar time standard by international agreement

Recommends

1. the relationships between the possible versions of a **lunar reference time scale** and other time scales, in particular a **lunar coordinate time** and UTC, are pursued in collaborative agreement among the relevant international organizations.

We are asking the international timing community to define terminology and standards for lunar reference time!!

- **Different approaches are under discussion**

- Be Interoperable by definition.
- Be traceable to Coordinated Universal Time (UTC)
- Consider the possibility of physical realization with infrastructure deployed on the Moon (long term)

- a phased approach needs to start from an agreed upon mathematical model
- Lunar time aligned to UTC (proportional to UTC + PL)

- Proper time from clocks in the cislunar environment

40